Improvement of Response Surface Quality for Full Car Frontal Crash Simulations by suppressing Bifurcation using Statistical Approach

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Abstract

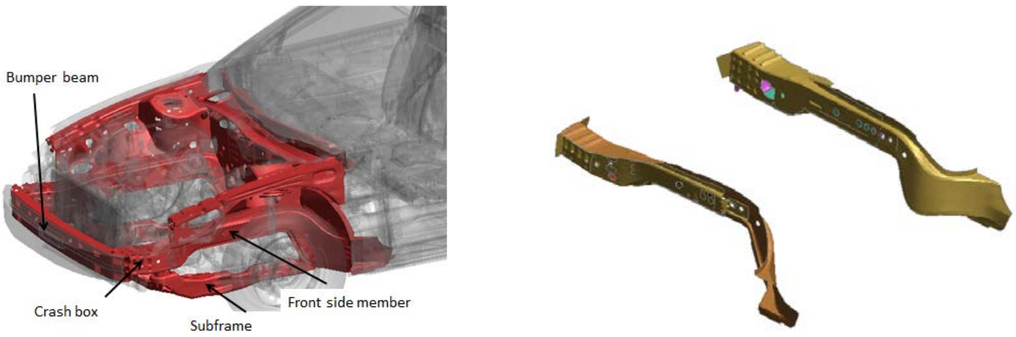
In recent years, importance of optimization is rising in automotive industry, since needs in fulfilling conflicting requirement such as light weight, rigidity, and safety in high level are continuously increasing, while car structure becomes complex due to new material and new connection techniques. RSM (Response Surface Method) is one of key technology for the purpose, and various approaches have been made.
However, quality of response surfaces tend to be poor when it comes to frontal or rear crash where contact and buckling is dominant, since bifurcations in behavior bring high non-linearity to response surfaces. One measure is to increase the number of simulation runs in order to improve the accuracy of response surface, but as the size of full car simulation models becomes bigger, it is not realistic to run over 100 times.
The fundamental problem is that the response surface is with high complexity due to bifurcations such as buckling and contact so that trying to fit highly non-linear response surface by adding points is not the absolute solution, but to reduce non-linearity of the surface in order to make it easy to fit.
In this study, scatter propagation mechanism is visualized based on statistical calculations, and structural design of front structure of an automobile is enhanced in order to suppress bifurcations with help from a statistical analysis software DIFFCRASH. Triggers of bifurcation are located and mechanisms of the bifurcations are studied, and design modifications are made to stabilize the deformation modes.
As a result, the complexity of response surface has been reduced, and accuracy of the response surface has been improved.

1 Design exploration of frontal crash simulation

In current automotive industry, safety and environment performance are the major driving forces for technology development. As car structures become complex, fulfilling conflicting requirements such as light weight and safety needs helps from optimization using RSM(Response Surfaces Method). RSM is commonly used for optimization, and various theories have been proposed such as RBF(Radial Basis Function) and FNN(Feedforward Neural Network)[1].
However, as car body becomes more and more complex, accuracy of prediction by response surface tend to become poor especially in frontal and rear crash where axial crush of longitudinal members are dominant so that potential of response surface method is not fully utilized.

1.1 Quality assessment of the response surface

Fig.1 shows the frontal crash FE simulation model for USNCAP full flat case (NCAC Ford Taurus) used for the study. Front side members highlighted absorb energy and the firewall protects passengers so that minimum intrusion of firewall is one of important requirements for occupant safety design.
In this study, thickness of 6 parts of front side members have been varied as design variables, and floor intrusion has been chosen as response variable to be predicted.



(a) Engine room of NCAC Ford Taurus model (b) 6 parts from the front side members to be studied

Fig.1: Design parameters of frontal crash model

Parameter	Range [mm]
Thickness - Inner L	1.0 – 3.0
Thickness - Outer L	1.0 – 3.0
Thickness - Reinforce L	1.0 – 4.0
Thickness - Inner R	1.0 – 3.0
Thickness - Outer R	1.0 – 3.0
Thickness - Reinforce R	1.0 – 4.0

Table 1: Configuration of 2 significant erroneous predictions

A quasi-Monde Carlo simulation with Latin-Hyper Cube method has been conducted with LS-OPT, and response surfaces have been built up with Radial Basis Function. Fig. 2 shows results of the accuracy of the response surface in PRESS residuals[2]. Vertical axis indicate predicted response by RSM, and horizontal axis indicate calculated response.

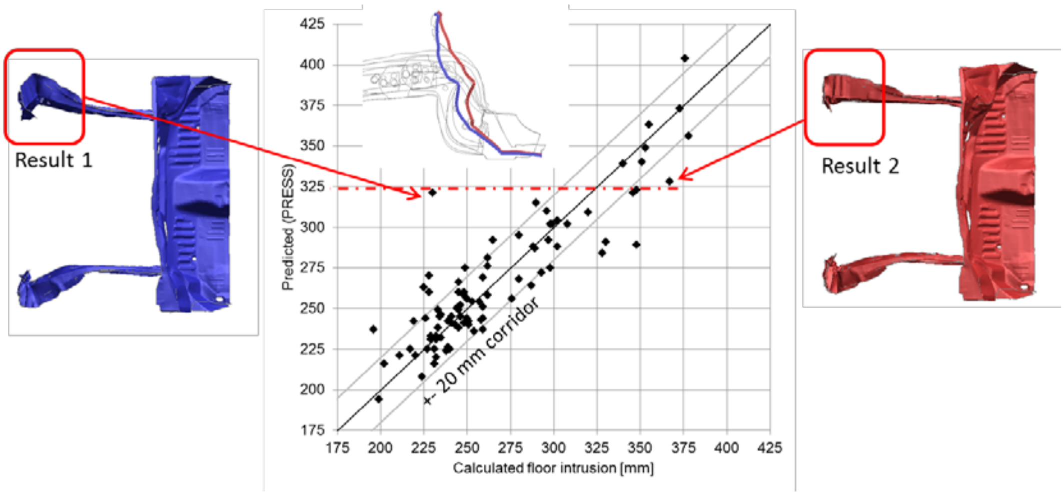


Fig.2: Response surface accuracy of the floor intrusion

There is an area where error is significant around 325 mm in intrusion. Calculated value of result 1 is 230mm, and result 2 is 367mm while the predicted value is around 325mm. This indicates there is instability in the system. 2 animation results where high level of error is observed. Result 1 shows bending in crash box, but result 2 shows axial crush on the other hand. Dominant design variables are studied by sensitivity analysis with LS-OPT as shown in Fig. 3. They are quite close to each other as shown in Table 2 but response shows 137mm of difference. This means there is a peaky region on response surface which is difficult to predict.

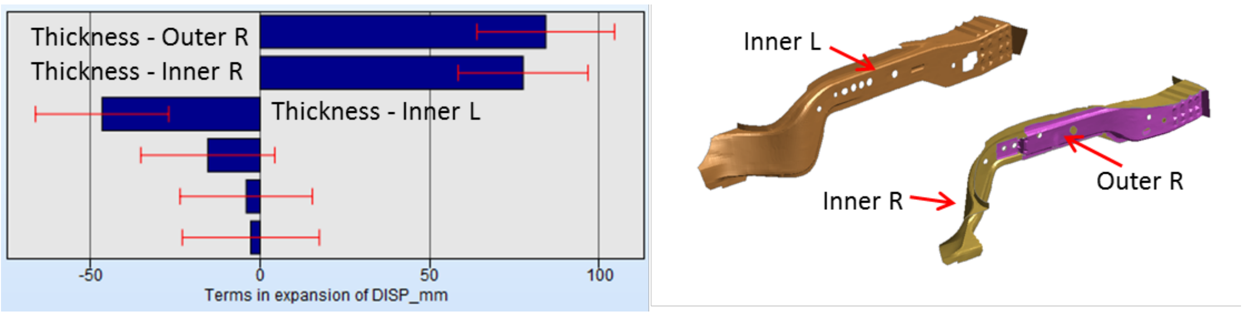


Fig.3: Sensitivity analysis of the part thickness on the floor intrusion

Parameter	Result 1 (blue)	Result 2 (red)
Thickness - Outer R	2.72	2.75
Thickness - Inner R	2.21	2.28
Thickness - Inner L	2.13	1.57
Floor intrusion	230 [mm]	367 [mm]

Table 2: Configuration of 2 significant erroneous predictions

There are two conventional approaches for achieving better accuracy of the response surface. The first one is to introduce more sophisticated meta-model theory and evaluation criteria. The second approach is to increase number of samples by using HPC(High Performance Computing) or by reducing computation time by simplifying the model. However, they have the following issues.
More sophisticated meta-model tend to be more sensitive to noise as RSM try to fit all samples even with error. The performance depends on selection of parameters which depends on engineers' skill and experience. Increasing number of runs is not realistic, since single full car simulation runs overnight in many cases. Use of simplified model will increase accuracy to the RSM, but there is a hidden risk of error between full model and simplified model.
The approaches above try to adapt to complex problems by adding complexity to the solution, but source of the problems is the complexity of the system itself so that absolute solution should be reducing complexity of the system.
In this paper, a statistical approach is applied to detect sources of complexity and remove it from system in order to improve prediction accuracy of response surfaces.

2 Robustness study of the model

Errors observed in the response surface are assumed to be due to instability of the model so that robustness study of the FE model is conducted. Strength of spotweld and thickness of parts in front area have been varied with realistic range (thickness +-5%, spotweld strength +-15%) as shown in Fig. 4. Natural scatter obeys Gaussian distribution, but in order to induce worst case, uniform distribution has been given.

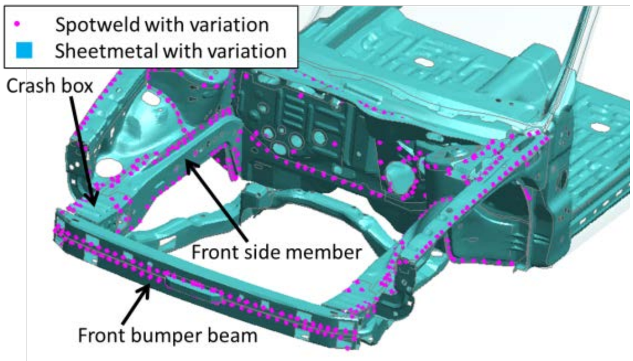


Fig.4: Scatter given to the model

Fig.5 shows scatter of floor intrusion from 30 runs. It is observed that the maximum scatter in intrusion around 80ms is originated in bifurcation around 20ms. Bifurcation causes instability in response and add complexity to the system. If the bifurcation is suppressed, the complexity of the system is reduced so that it becomes easier for standard response surface theory to fit.

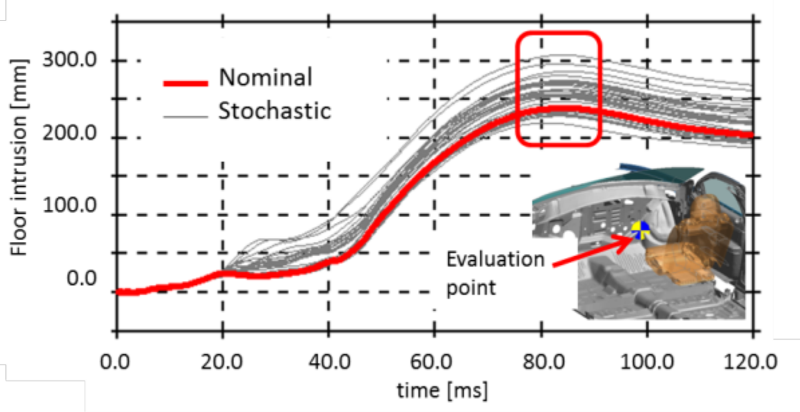
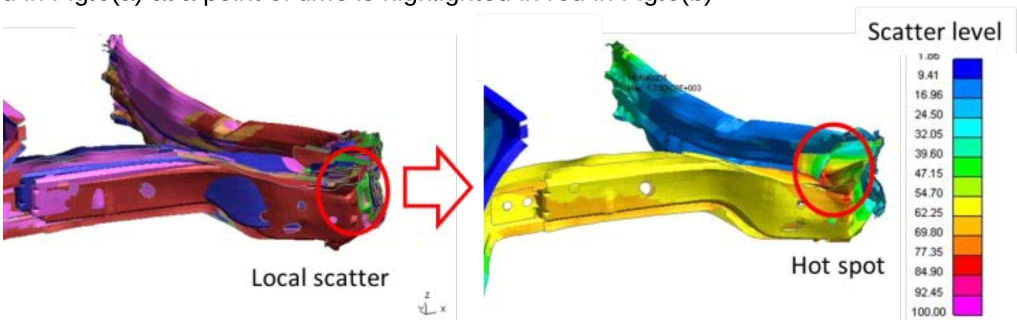


Fig.5: Scatter in floor intrusion

2.1 Visualization of scatter by using statistical approach

In this study, a statistical analysis software DIFFCRASH[3] has been used to visualize scatter level embedded to animation plot. Fig. 6 shows schematics of visualization by DIFFCRASH. Local scatter observed in Fig.6(a) at a point of time is highlighted in red in Fig.6(b)



(a) Overlaid 5 simulations (b) DIFFCRASH visualization

Fig.6: Schematics of scatter visualization with DIFFCRASH

A remarkable increase of scatter level is observed at 14ms as shown in Fig.7 by checking through the animation from 0ms to 30ms. This means some simulation results in 30 runs started to show different behavior. The area of high scatter level grows through right front side member and reaches to the firewall at 30ms. This indicates the correlation between scatter in floor intrusion and scatter initiation in right crash box at 14ms and it is assumed that suppressing the scatter initiation could reduce the scatter in floor intrusion.

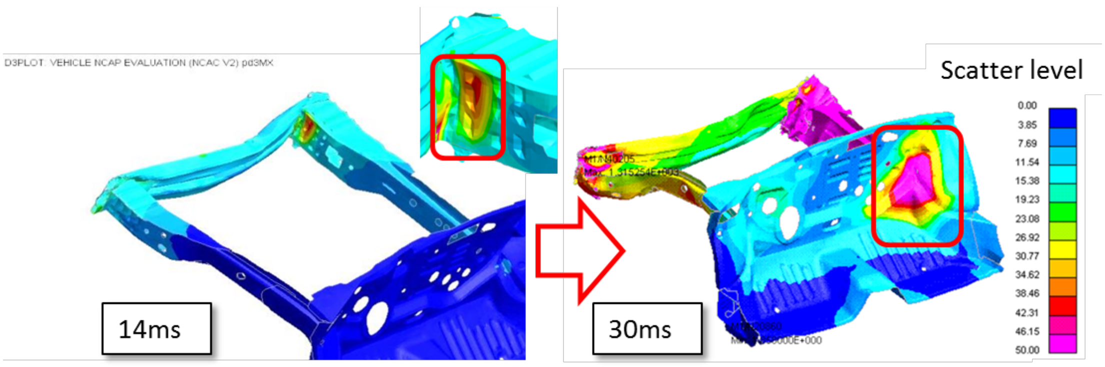
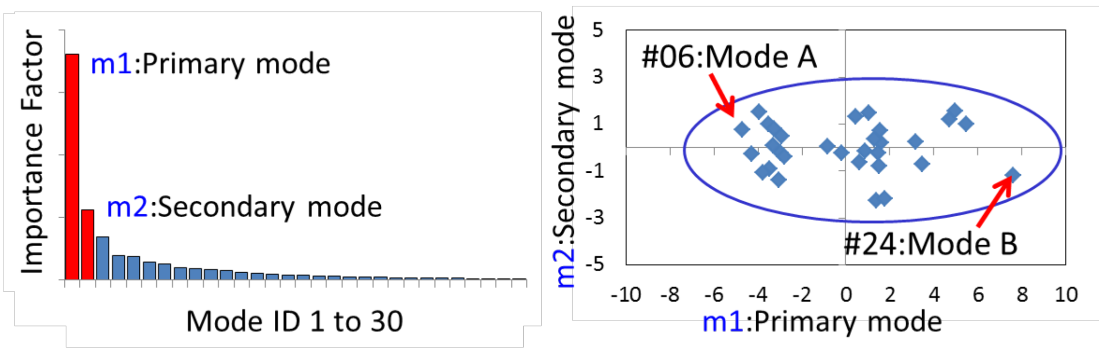


Fig.7: Scatter contour plot

2.2 Principal Component Analysis of the scatter

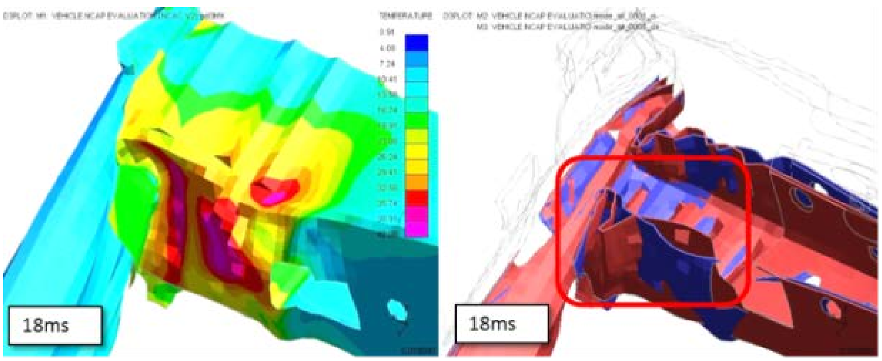
It is essential to know the characteristics of the structure in order to understand scatter mechanism. In this study, a concept of experimental modal analysis which is used in NVH field has been introduced. In experimental modal analysis, mechanical input such as impulse, sweep sine curves is imposed in order to excite the structure in whole frequency range so that the “deformation modes” are extracted. For robustness analysis, dozens of dynamic simulations are conducted with slightly different conditions and superpose the results so that the “scatter modes” are extracted.
Although automotive frontal crash simulation is a highly non-linear problem, by focusing only on the coordinate of a node in 1 direction at a point of time, results from several calculations can be described as a cloud on the number line so that statistical values such as mean and variance can be calculated to form a covariance matrix for entire structure. Covariance matrix is known as semidefinite so that eigenvalues are greater than 0, and eigen analysis of the covariance matrix yields eigen values and eigen vectors[4]. Eigen value represents the level of scatter, and eigen vector represents trends of scatter in terms of deformation at the point of time.
PCA (Principal Component Analysis) for the 30 simulation results at 30ms has been conducted. Fig. 8(a) shows the 1st and 2nd dominant modes, and Fig. 8(b) indicates the cloud plot of the contribution factors in mode-1 and mode-2 direction. In this study, mode-1 is quite dominant compared with mode-2, and run #6 and #24 are the 2 extreme results which represents the scatter behaviour in this model at 30ms.



(a) Importance of modes (b) Cloud plot of simulations in modal space

Fig.8: Result of Principal Component Analysis (30ms)

The animations of run #6 and #24 are compared with the scatter contour plot in Fig. 9. It shows that the area with high scatter level shows clear bifurcation in behaviour of the crash box. This bifurcation results in large difference in floor intrusion at 80ms.



(a) Scatter contour (b) overlay of #6 and #24

Fig.9: bifurcation in collapse mode at the crash box

Deformation in mode B(#24) shows insufficient axial crush and force acting on floor is greater. On the other hand, Mode A(#6) shows outward bend and force applied to firewall is relatively small. Other results on the plot are assumed to be in between the 2 results.

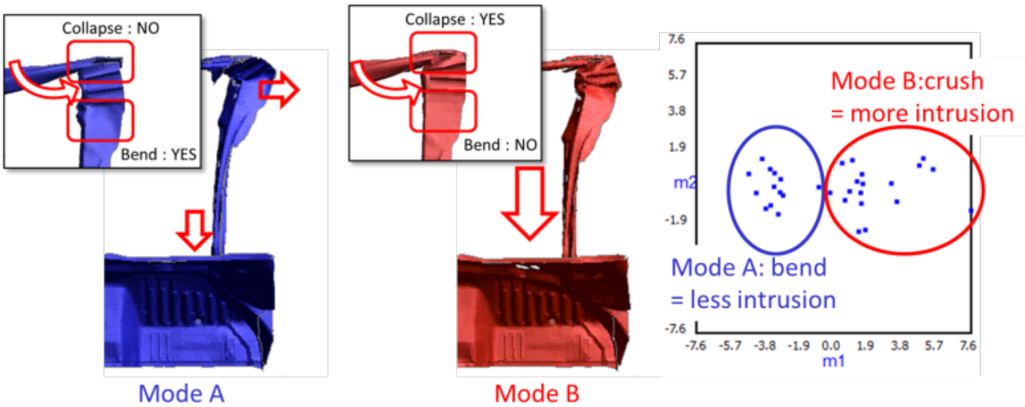


Fig.10: Result of mechanism analysis

2.3 Design improvement for inducing favourable mode

For real product design, opinions from other functions needs to be taken in to account, and crash box is supposed to show clear axial crush to absorb energy. However, the objective of this study is to showcase a new approach so that mode A, which shows less intrusion, is defined as the favoured mode. With this definition, the purpose of design modification is to increase the ratio of mode A which is a minority in Fig. 10. Fig. 11 shows the modification to the crash box in order to induce bending outward.

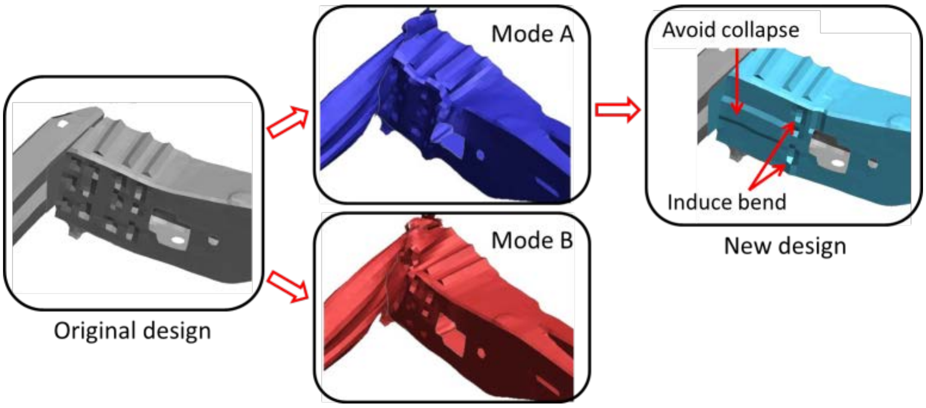
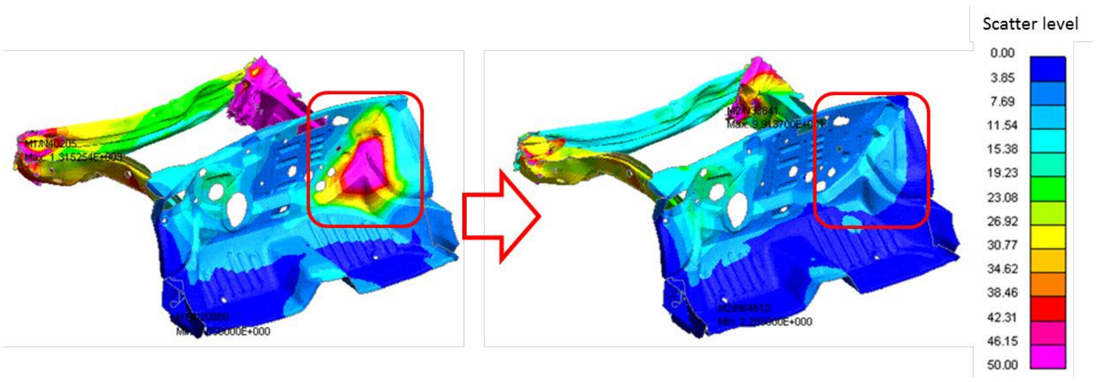


Fig.11: Design modification for inducing mode A

Another set of simulation with identical parameter set is conducted and the results are processed with DIFFCRASH in order to assess the effect of the design modification. Fig. 12(b) shows significant reduction of scatter compared with Fig. 12(a) due to unification of deformation of crash box. However, scatter in left hand side became dominant so that iterative modifications are needed..



(a) Original design (b) Improved design

Fig.12: Reduction of scatter level of floor intrusion

The same approach has been applied to the left hand side, and the design modification is made. Fig.13 shows the floor intrusion from 30 runs. Deformation mode of left and right crash box has been unified to favourable modes so that scatter of floor intrusion is significantly reduced compared with Fig.5 and the level of maximum intrusion is also reduced to 260mm.

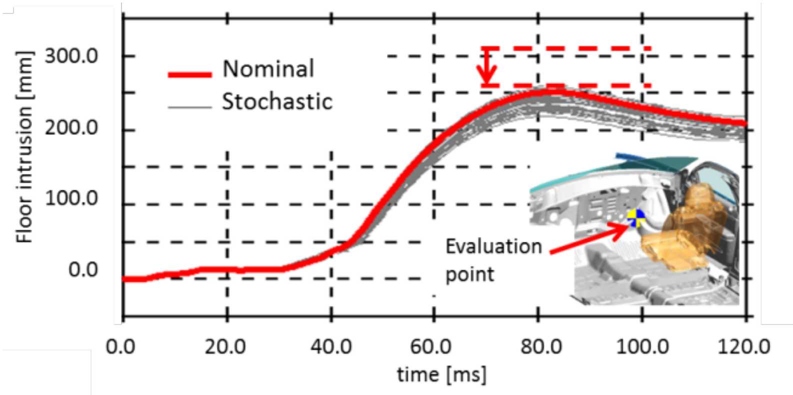
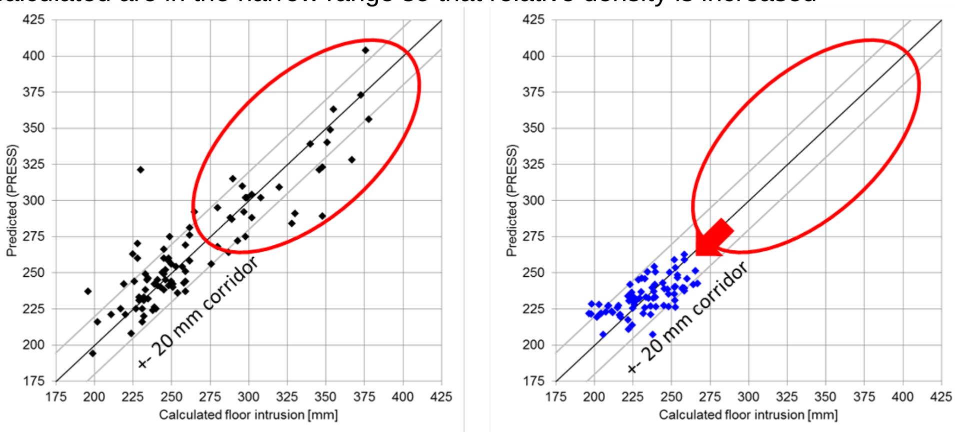


Fig.13: Floor intrusion after 2 design changes

3 Effect of robust design improvement to response surface

Fig. 14(a) shows the accuracy of the meta-model from the original model, and (b) shows the one from the modified model. Not only the error is reduced so that most of points are within 20mm corridor, but also the range is shrunk from [180mm, 410mm] to [180mm, 270mm]. This is due to selection of favorable mode which intends to reduce floor intrusion. There is no significant error as shown in (a) around 325 mm in (b), since complexity of the system has been reduced.
Table 3 shows the evaluation of the RSM in terms of COD (Coefficient of Determination), RMS(Root Mean Square) error, and PRESS. The reason why the COD is worse for the modified model is the followings.
The denominator of COD represents the range of the response and numerator represents the band width of the cloud. Since the range of the response is reduced less than a half, the cloud in (b) becomes more round compared with the cloud in (a), and as a result, COD becomes lower. For the discussion above, COD is not appropriate for assessing quality of response surface in this case.
On the other hand, both of PRESS and RMS error shows better result in the one from the modified model. The followings are possible reasons.

1. The range of response is narrower so that there is less risk of overshoot
2. Instability around 325mm is eliminated from the scope of the response surface
3. All the calculated are in the narrow range so that relative density is increased



(a) Original (b) modified

Fig.14: Accuracy of response surface (LS-OPT : Radial Basis Function)

	Original	Modified
Coefficient of Determination	0.829	0.448
PRESS	20.2 (7.61%)	13.7 (5.87%)
RMS error	15.4 (5.8%)	12.5 (5.37%)

Table 3: Effect of robust design improvement to response surface accuracy (Radial Basis Function)

4 Summary

In this study, a response surface for a frontal crash simulation is built up which shows instability in the system. Robustness study of the front area is conducted using DIFFCRASH, and trigger of bifurcation is located. The nature of the structure is analysed with PCA and favourable deformation mode is defined. Design modification is made to the source of instability in order to guide deformation to the favourable mode. Another response surface is built up and improvement of prediction accuracy is confirmed in terms of PRESS and RMS error.

5 Literature

[1] Ortmann, C. and Schumacher, A.: “Meta-models in structural optimization - techniques and strategies“, Proceedings of the Automotive CAE Grand Challenge 2014, 2014

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